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When experts disagree: Using the Policy Delphi method to analyse divergent expert expectations and preferences on UK energy futures

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Highlights

- Significant levels of expert disagreement are found over UK energy system futures
- Buildings' heating and personal transport futures are particularly contested topics
- Policy Delphi is useful to reveal the extent and range of expert disagreement
- Expert views reflect parametric and structural uncertainties and value differences
- More evidence, and evidence reviews are unlikely to fully resolve expert differences

Abstract

Recent literature has highlighted the need to critically examine the assumptions and values that influence scenario analysis and expert advice on contested topics. To this end, this paper presents the results of a large scale two-round Policy Delphi expert survey on UK energy futures. The survey constitutes one of the most detailed and wide-ranging analyses of UK-based energy researchers and stakeholders (policy makers, businesses and civil society groups). Through a quantitative and qualitative analysis of expert views on two particularly challenging and contested topics (the future of heating provision in buildings and the future of personal transport), we develop an understanding of the extent of expert disagreement and the reasons behind it. For both heating and transport cases, disagreements and uncertainties emerged in terms of a number of specific parameters (particularly related to technical performance and the feasible pace of technology diffusion) and structural uncertainties (related to system boundaries, sociotechnical dynamics and the endogenous role of policy), and also epistemic and normative differences among participants. By setting out the diversity of expert views and reasoning on contested issues, Policy Delphi can help decision-makers

understand expert disagreement, and how it is associated with different epistemic and normative perspectives.

Section 1: Introduction

While climate experts agree to a very high extent in their assessments of the likely causes and geophysical impacts of climate change (IPCC, 2018), the necessary response – in terms of the future of energy systems around the world – is much more contested. This is understandable: energy systems are complex and multi-scale networks of technological infrastructure, public and private organisations, institutional rules and social and community practices (Hughes, 1983; Geels, 2002). As a result, a diverse and dynamic pattern of drivers and responses play out across different aspects of the system, in production, distribution and consumption, and different energy services such as heating and transport. This renders energy futures indeterminate and open to divergent expectations.

Many analysts anticipate highly disruptive futures for energy systems, in the context of ambitious national and international policy targets for decarbonisation (such as the 2016 Paris Agreement on climate change), emerging technological changes, and wide-ranging societal, behavioural and demographic trends (e.g. Energy Institute, 2017; PwC, 2016; Wilson, 2018). At the same time, energy systems have historically exhibited continuity-based change, in terms of the renewal and adaption of existing infrastructure and organisations (Van der Vleuten and Högselius, 2012; Winskel and Radcliffe, 2014; Winskel, 2018). Alongside disruptive visions, a 'repurposing' narrative is also evident in recent thinking about energy futures (e.g. Howard and Bengherbi, 2016).

This article presents results from a detailed Policy Delphi survey which explored the nature of the UK's future energy system transition over the next two decades as it responds to the challenge of deep decarbonisation. Although the survey covered many different aspects of the UK energy system transition, we focus here on two contested aspects: buildings' heating and personal transport. We pay particular attention to mapping disagreement on some key aspects of the transition, the expression of disagreement in terms of parametric and structural uncertainty, and the role of underlying values and assumptions in shaping disagreement.

A key feature that distinguishes Policy Delphi from conventional Delphi survey designs is its focus on understanding disagreement within an expert community. According to de Loë et al., Policy Delphi designs are intended to "identify opposing positions and opinions on policy questions" (de Loë et al., 2016, p. 79), setting out the range of perspectives on a complex issue. Similarly, Coates has argued that Delphi methods are valuable for presenting participants with the complexity of issues and diversity of expert views, and thereby providing an opportunity to challenge their assumptions (Coates, 1975). For these authors, understanding the reasons why experts disagree is at least as important as identifying areas of consensus. Despite this, expert disagreement remains under-reported and under-theorised in many Policy Delphi studies.

Since long-term decisions on energy policy need to be taken despite such uncertainty, a Policy Delphi survey was designed to explore expert and stakeholders' views on how disruptive and continuity-based 'logics' are likely to play out in contrasting scenarios for the UK energy system over the next two decades, up to 2040. Both scenarios involve major changes – a 'system transition' (Geels, 2002) – in response to policy and other drivers, but the social and technical system dynamics involved are very different under the two transition logics.

Under a disruption-based transition, new technologies, business models and behaviours provoke a fundamental remaking of the UK energy system. Existing organisations and infrastructures are unable to respond sufficiently to disruptive forces affecting the sector, and are destabilised and then displaced. Digitisation and smaller scale generation and storage drive a rescaling and decentralisation of the system, both technically and institutionally, with regional and city/local authorities becoming key energy strategists. In this scenario, consumers might also become more influential in the energy system transition, for instance as prosumers or through active demand-side management becoming mainstream.

Alternatively, under a continuity-based transition logic, system transition is pursued mainly by adapting and repurposing existing organisations and infrastructures. New technologies, business models and behaviours are adopted, but as extensions and adaptions of existing ones. For the relatively highly centralised UK energy system, this would mean that economies of scale in technological and organisational form remain important. Smart technologies are introduced, but without fundamentally disrupting or rescaling system operation and ownership. Similarly, the system remains subject to a high degree of national strategic direction, and citizen engagement remains limited.

In this paper we use these transition logics as heuristic tools for revealing differences in expert reasoning, including parametric and structural uncertainties and value differences. The paper proceeds as follows: the next section reviews how expert disagreement is understood within the Policy Delphi literature, and outlines the range of reasons why experts and stakeholders disagree on complex sociotechnical systems; Section 3 sets out the methodological approach used for conducting and analysing our two-round Policy Delphi study; the survey findings on buildings' heating and personal transport are reported and discussed in Section 4 and conclusions are presented in Section 5.

2: Understanding expert disagreement in complex sociotechnical systems

2.1. Expert disagreement in Policy Delphi studies

Understanding why experts disagree is a defining feature of Policy Delphi studies. There is, however, no agreed method for analysing and/or presenting the reasons for expert disagreement in the research literature. Writing in 1975, Coates observed that researchers do not tend to report the diversity of experts' judgments and their underlying assumptions, adding that "more attention should go into the basis of divergence rather than the basis of convergence" (Coates, 1975, p. 194). Since then a variety of approaches have emerged.

One common approach is to group similar answers together (either through cluster methods, factor analysis or similar tools), and thereby build a theoretical model that accounts for a wide range of factors in a system (e.g. Steinert, 2009), or construct alternative visions of the future (for example, Tapio, 2003). This approach is useful for summarising a range of expert perspectives, and embodies a recognition that the pursuit of simple solutions and expert consensus in the context of complex problems is misguided (Collingridge and Reeve, 1986; Funtowicz and Ravetz, 1993; Stirling, 2010). However, a weakness is that typically little attention is paid to the diversity of participants' underlying reasoning. Tapio, for example, notes that as a result of using cluster analysis, some participants who reached similar conclusions but for different reasons were placed in the same category in his analysis, undermining the coherence of the clusters generated (Tapio, 2003, p. 98).

Others place a greater emphasis on understanding the full range of participants' reasoning when reporting their Delphi studies, highlighting where and why participants disagree (e.g. Banwell et al., 2005; Pätäri, 2010; Landeta and Barrutia, 2011; van de Linde and van der Duin, 2011). For Landeta and Barrutia (2011), this was an important output for decision-makers, as their study was designed to reveal the differences in opinions and perspectives from across the Basque university community, so as to inform the development of new university structures and processes. Similarly, in a study designed to elicit expert views on the processes of radicalisation and extremism in the Netherlands, Van de Linde and Van der Duin highlighted factors that only a minority of experts considered important, and argued that they require more attention (2011, p. 1562). Pätäri (2010) presented a detailed analysis of the key drivers shaping the bioenergy sector, associated business models, and the role of different companies

(Pätäri, 2010). The author used quotations to reveal points of expert disagreement and perceived contingencies, providing a broad overview of the varied issues and perspectives that emerged in the survey.

Such studies resonate with Stirling's observation that while researchers sometimes assume policymakers desire simple answers, it is often more helpful to be presented with an overview of the range of positions and perspectives on a given issue, reflecting the complexity and the full range of possibilities and implications (Stirling, 2010). Yet, while there is increasing recognition of the value of mapping how and why Policy Delphi participants disagree, more attention should be paid to the divergent reasonings underpinning disagreement. For example, if experts disagree because they refer to different sources of evidence then this implies a need for efforts to synthesise the evidence base. Secondly, if disagreements reflect uncertainties in the available evidence then new studies may be needed. Finally, in cases where differences in *values* account for differences in experts' assessments, then new evidence or evidence synthesis are unlikely to resolve matters, and value differences should be made explicit in the policy debate (Pielke Jr, 2007; Stirling, 2010). The next section draws on literature from energy scenarios and the sociology of expertise to further examine the range of reasons why experts disagree.

2.2. Assessing the future in complex sociotechnical systems: parametric and structural uncertainties

In the UK and internationally, decision-makers have relied upon energy scenarios for decades to understand how complex sociotechnical systems may change under different conditions (Hughes and Strachan, 2010). For example, in the early 2000s, scenarios derived from the MARKAL energy model were used to support and strengthen the UK Government's 2050 targets for carbon emissions reductions by demonstrating that the targets are technically and economically achievable (Strachan et al., 2009).

While Derbyshire and Wright (2014) have suggested that rather than developing scenarios, a better way for organisations to handle deep uncertainty is to construct 'antifragile' strategies that mitigate against losses from the worst possible set of outcomes, in practice governments and others seeking to steer the energy system transition often remain reliant upon experts' assessments of what types of changes are possible and desirable. As such, despite the indeterminacy of the future, scenarios informed by expert views are likely to maintain an important role – not as predictors of the future, but, as Eyre and Barauh (2014) have argued

– as tools to broadly describe the uncertain space within which actual futures are likely to develop.

Yet while decision-makers are attracted to scenario development because of the challenges of making decisions under conditions of complexity and uncertainty, these same conditions make it likely that experts will disagree. Funtowicz and Ravetz defined the term 'post-normal science' to characterise such circumstances, in which policy-makers are tasked with making time-sensitive and high-stakes decisions on a complex topic in a context of uncertainty over the facts and disputes over values (Funtowicz and Ravetz, 1993). A better understanding of the different reasons why experts disagree under conditions of post-normal science may offer improved ways to understand Policy Delphi results, and their implications.

A relatively simple reason for disagreement in expert views of how a complex system is likely to change relates to their assessments of specific parameters. A group of experts may agree on a shortlist of key quantifiable parameters as shaping the future development of a system, yet disagree on the value of those parameters – for example, how a population size and form will change, or how the cost and performance of specific technologies will change. This 'parametric uncertainty' (Hughes et al., 2013, p. 47) can result in experts reaching different conclusions on the future development of a system.

In addition, there is also the uncertainty that arises due to the multiple ways in which the different parts of a complex system are defined and interact with each other – known as 'structural uncertainty' (Trutnevyte et al., 2016). Structural uncertainties arise from indeterminacies over how different parameters interact, but also from which parameters matter most, how problems are framed, how system boundaries are defined, and the different pressures driving change. For example, technological innovations may be brought to market in different forms, under a range of public support measures and private business models, and be shaped by a variety of broader societal and demographic trends – resulting in an indeterminate array of possible outcomes (Hofman and Elzen, 2010; Hughes et al., 2013). Analysts can therefore agree in their assessment of what the important factors are but differ in their view of how they are most likely to interact to produce a single (or limited number of) future outcome(s).

Expert disagreements over parametric and structural uncertainties reflect differences in epistemic and normative views. These differences have a number of origins. Large complex systems are often analysed using interdisciplinary analysis, because different disciplinary perspectives or 'paradigms' bring different features into focus while marginalising or 'blackboxing' others (Kuhn, 1970; Pinch, 1992; Jasanoff, 2004). By necessity, different disciplinary perspectives operationalise distinct descriptive and normative assumptions about how the system works and what the role of actors, technologies, and organisations is therein. Consequently, researchers working in different disciplines may come to define a problem and its system boundaries in different terms. For instance, economists and energy modellers often operate under a 'cost-driven paradigm' where actors are assumed to act uniformly in predictable and rational ways (Li and Pye, 2018), whereas sociologists often reveal diverse and surprising ways in which actors engage with specific technologies and shape their development in practice (see, for example, a typology of solar panel users, in Ghanem and Haggett, 2011). Differences in experts' assessments of parameters and structural considerations may therefore reflect the different disciplinary lenses and associated assumptions which influence their observation of the given system.

In addition to the intrinsic assumptions within a field, researchers also rely on a set of heuristics that may go unchallenged within their community. For example, during the oil crisis energy scenario developers predominantly focused on exploring the implications of variations in fossil fuel prices, economic growth, and energy demand, while after nuclear power plant accidents they began exploring the potential implications of removing such power plants from the system (Trutnevyte et al., 2016). These prioritisations may be compounded further by individuals' (or indeed a community's) technological optimism (Dorr, 2017) as well as their models of how social and technological drivers of change interact.

Researchers may implicitly ascribe to a view of technological determinism, according to which technology diffusion determines changes in social practices (Winner, 1980) or lean more towards social determinism – the view that social and cultural values and practices are the key drivers shaping the emergence and manifestation of a technology in a society. In an example of the latter relevant for the present study, Hughes and Strachan report that some modellers have associated the diffusion of distributed energy generation technologies with a dominance of community values (Hughes and Strachan, 2010), when in practice it is possible that distributed generation technologies are adopted independently of any rise in community values. Such assumptions have been found to be reinforced in scenario communities through the use of specific heuristics (e.g. availability, recency, saliency and familiarity) (Bradfield, 2008; Hughes and Strachan, 2010; McDowall et al., 2014; Li, 2017; Li and Pye, 2018).

Alongside these shared assumptions and heuristics, underlying values also shape individual assessments of uncertain and contested outcomes. From a 'cultural theory' perspective, these values influence how individuals interpret risks and judge appropriate societal responses

(Douglas and Wildavsky, 1982; Thompson 1984; 1990). According to this view, varied orientations towards factors such as social coordination, group collaboration, personal choice and rule imposition are associated with distinctive 'worldviews': fatalists, individualists, hierarchists and egalitarians. As many studies have shown, experts involved in policy controversies may disagree in similar ways to the wider public in their interpretations of the evidence base, acceptable levels of risk and appropriate societal responses (Nelkin, 1975; Jasanoff, 1990; Sarewitz, 2004; Hulme, 2009). Moreover, in their expert elicitation exercise, Pye and colleagues found that values have a more influential impact on experts' long term estimates than short term estimates (Pye et al., 2018).

In summary, experts' expectations of how a complex energy system may develop will vary according to differences in their assessments of parameters and structural features, and these differences in turn reflect a range of assumptions, heuristics and values.

2.3. Implications for resolving disagreement

The previous section suggests that expert disagreements on complex issues cannot always be resolved with more evidence. However, structured and open dialogues between scenario developers and other experts and stakeholders can help to identify implicit assumptions and heuristics, and thereby facilitate learning (Funtowicz and Ravetz, 1993). Hughes and Strachan identified a need for more open engagement in the construction of scenarios, to allow the researchers and decision-makers' assumptions to be challenged, because otherwise "[they] can prevent decision-makers from considering the possibility of undesirable outcomes", thereby exposing themselves to unmitigated risks, missed opportunities and "tunnel vision" (Hughes and Strachan, 2010, p. 6057). Similarly, Li and Pye identified a need for energy policy design to "escape from caged thinking concerning what can or cannot be included in models and therefore what types of uncertainties can or cannot be explored" (2018, p. 130).

These arguments resonate with literature in the field of Science and Technology Studies, which has highlighted the importance of epistemic diversity and constructive challenge for facilitating learning within expert and policy communities (Rip, 2003; Kattirtzi, 2016). Researchers here have argued that policy-makers find it valuable to be presented with diverse experts and stakeholders' views on a contested topic, as it provides them with a broader understanding of the evidence and of the range of issues at stake (Pielke Jr, 2007; Stirling, 2010). In addition to these 'substantive' reasons for promoting diversity, there is also the 'normative' argument that giving voice to a wider variety of perspectives in a process intended to inform policy constitutes good political process in a modern democracy (Stirling, 2008).

3: Research Design

Formed as part of a wider project carried out by the UK Energy Research Centre (UKERC), the two-round Policy Delphi study reported here was conducted between late 2017 and early 2018. Panellists were recruited from three communities: the UKERC interdisciplinary research community; a wider interdisciplinary group of UK-based academic researchers and stakeholders, and representatives from government and parliamentary bodies, industry and non-governmental organisations. They were recruited using a UK Research Council database of energy researchers, stakeholder lists developed by UKERC, and through a snowballing technique (Bryman, 2016) with assistance from across the UKERC membership, in order to ensure we reached a wide and varied energy stakeholder community. This involved an active effort to strike a balance between niche actors and organisations, alongside more established ones.

The survey topic statements were developed through several months of desk-based research and collaboration between the authors, through advice and feedback at a project steering group, as well as a pilot phase with the UKERC research community in summer 2017. Following Miles et al. (2016, p. 102) and with a keen awareness of the diversity of our intended sample across different disciplines and professions, we developed topic statements that were as far as possible succinct, precise, unambiguous, devoid of confusing jargon or loaded terms, while at the same time being credible, inclusive and amenable to diverse responses. The surveys were administered online using Qualtrics software.

Under each survey topic, participants were asked to assess the likelihood of different propositions about the UK's energy system in 2040. Inspired by de Loë's model for Policy Delphi studies (de Loë, 1995), participants were asked to assess the propositions on a 4-point Likert scale with an additional option of 'undecided/cannot say'. They were then asked to explain the reasoning behind their answer, with reference to relevant supporting evidence. In this way, the survey went beyond merely capturing the diversity of expectations amongst experts, but also enabled us to understand the reasoning and contingencies underlying these differences.

In line with other Policy Delphi studies, there was a decline in participants between the first and second round (Gordon, 1994; van de Linde and van der Duin, 2011): 127 participants completed the first round survey – although participants sometimes skipped questions, possibly due to a lack of relevant expertise, time limitations and/or felt fatigue (Dayé, 2018). Over half (54%) of Round 1 participants (n=69) also took part in Round 2. To minimise participant fatigue, some questions on topics where consensus was high in Round 1 were omitted in Round 2. In addition, rather than presenting all Round 1 participant comments to all respondents for each question in Round 2, each participant was instead presented with a frequency table of the Round 1 participants' assessments, a concise summary of the range of arguments deployed, and her/his own previous quantitative and qualitative answers. They were then given the opportunity to change their Round 1 response, and offer any additional comments. Since a Policy Delphi does not seek to establish consensus, the process ends once views have been judged to have stabilised, which in this case – given the limited instances of changed views between Rounds 1 and 2 (see Section 4) – occurred at the second round.

The data was analysed in SPSS and NVivo 11 software packages. For the quantitative Likert scale data, we applied de Loë's (1995, p.62) consensus measure to calculate the extent of consensus reached for each statement. As shown in Table 1, this measures consensus on a scale between 'none' and 'high', depending on how the responses are spread across the categories (highly unlikely, unlikely, likely or highly likely), taking into account that there are contiguous categories (i.e. likely *and* highly likely; or unlikely *and* highly unlikely). For example, a statement would have a 'high' consensus score if either 70% of the valid answers are in a single category, or if 80% of the valid answers are in two contiguous categories. Where the scores for one single category and across two contiguous categories differ, the statement is given the highest of the two scores.

Table 1: De Loë's method for measuring Delphi Survey consensus (de Loë, 1995)

Extent of consensus	***Minimum proportion of valid answers within one category***	***Minimum proportion of valid answers across two contiguous categories***
High	70%	80%
Medium	60%	70%
Low	50%	60%

The qualitative comments were systematically coded in terms of whether they supported the continuity or disruption scenario for that topic, and what assumptions and values they reflected.

4: Results

In this section, we present a selection of the survey results relating to two particularly challenging and contested parts of the UK energy system transition: heating in buildings and personal transport. In discussing the results, we treat the quantitative and qualitative data differently: while we present the quantitative results in full (in Tables 2 and 3 below), we discuss the qualitative data thematically so as to represent the diversity of perspectives offered in open text responses (Small, 2011).

4.1 Heating in Buildings

Introduction

At present, approximately 80% of all commercial and domestic buildings in the UK are connected to a national natural gas network for the supply of heat (Chaudry et al, 2015). In addition, energy use in buildings (including space heating, water heating and cooking) accounts for nearly 20% of the UK's carbon emissions (BEIS, 2018) and less than 5% of the energy used for heating buildings is produced from low carbon sources (Committee on Climate Change, 2019). The established way of providing heating for buildings in the UK cannot continue for much longer if climate policy targets are to be met (Committee on Climate Change, 2016). By 2050, the Committee on Climate Change has estimated that 90% of UK homes will need to be supplied by low carbon sources – i.e. excluding natural gas (Committee on Climate Change, 2019).

In this context, a variety of low carbon heat supply solutions are being considered, across different scales of infrastructure and governance. They include, for example, local / community -scale district heating networks (a potentially highly disruptive supply infrastructure for the UK, both technically and socially), a switch from domestic gas boilers to domestic electric heat pumps (which is disruptive at the level of individual buildings and also the electricity grid), or the repurposing of the UK gas distribution infrastructure, so that it can distribute low carbon gas for heating, such as hydrogen (a relatively continuity-based solution, at least for local infrastructure and domestic end-users). To address the disruptive or continuity-based possibilities for UK heating futures by 2040, participants were asked to assess the likelihood of three distinct propositions:

1. Local, municipal and community-based provision will dominate UK buildings' heating
2. National infrastructure will continue to dominate UK buildings' heating, with some repurposing
3. A patchwork mix of technologies at different scales will have emerged, but no single heating supply technology will dominate

The participants were asked to explain their answers with reference to sources of evidence where possible. The Round 1 results are displayed below.

Table 2: The likely pattern of buildings' heating in the UK in 2040

Buildings' heating propositions	**Highly likely**	**Likely**	**Unlikely**	**Highly unlikely**	**Cannot say / undecided**	**Total valid responses***	**Extent of consensus**	**Consensus View**
Local, municipal and community-based provision will dominate	2 (2%)	11 (11%)	56 (55%)	15 (15%)	18 (18%)	102	High	Unlikely/ Highly Unlikely
National infrastructure will continue to dominate	9 (9%)	54 (53%)	23 (23%)	1 (1%)	15 (15%)	102	Medium	Likely
A patchwork mix of technologies at different scales will have emerged	26 (25%)	52 (51%)	20 (20%)	1 (1%)	3 (3%)	102	Medium	Likely/ Highly Likely

* i.e. excluding 'undecided' / 'cannot say' responses.

As

Table ***2*** shows, 70% of all respondents considered that local, municipal and community-based provision is unlikely or highly unlikely to become dominant by 2040; 62% thought it likely or highly likely that national infrastructure would continue to dominate, while more than three quarters of all participants (76%) considered a 'patchwork mix' to be likely or highly likely. In terms of overall transition logics, this suggests that most participants anticipate a relatively continuity-based transition for buildings' heating in the UK up to 2040, with some emerging disruption.

Parametric uncertainties

One reason why participants disagree about heating futures is that their arguments rely on estimates of specific parameters which are uncertain and disputed. The two most frequently discussed (and contested) parameters in respondents' comments are the technical performance of the different types of heating provision, and the feasible pace of change in terms of the diffusion of low carbon solutions across the UK building stock. While a small number of participants reasoned that these parameters mean that it is too soon to decide which future pathway will prevail, most were able to identify a likely pathway, despite the limited evidence.

However, parametric uncertainty for buildings' heating was not narrowly restricted to assessing the cost, performance and diffusion rate for specific heating technologies. Participants also applied a range of technical and social performance criteria across sociotechnical infrastructures. For example, those who consider it likely that incumbent infrastructure will remain dominant tended to highlight the economies of scale and standardisation benefits associated with a single national infrastructure, the high costs of emerging alternatives, and the popularity of established technology amongst consumers:

> *"Making the best use of existing national infrastructure and assets (rather than building new ones at a local level) will minimise the disruption caused and additional costs incurred."*

Senior manager at an energy networks company

> *"The current vogue is to say that we need an array of solutions for heating. I don't buy that at all. All industries that deliver at low cost have high degrees of standardisation and economies of scale… I do not believe in a mix and I think the idea of a mix is muddying the debate a lot."*

Senior industry consultant

By contrast, those participants who anticipate a more disruptive transition (in terms of either a patchwork mix of solutions, or a more decisive transition to local and community based provision) not only questioned the technical and economic feasibility of repurposing existing infrastructure, but also highlighted the importance of local context in assessing the likeliest pathway (in that different technologies are better suited to different types of housing stock, local geography and communities):

> *"Different technologies make best sense in different settings… multiple solutions will co-exist."*

Professor of social science

> *"Due to geographic [and] demographic constraints (income levels, policy views) and the state of building stock, it is unlikely that one technology will dominate."*

Senior academic energy modelling researcher

As participants holding different views referenced different assessment criteria – scale economies and standardisation versus diversity and local 'fit' – they are unlikely to agree on a common evidence base to establish a consensus, or persuade each other to change view.

Structural uncertainties

Structural uncertainties for heating futures arise in a number of ways, in terms of interactions across different parts of the energy system and system boundaries. For example, in assessing the feasible pace of change by 2040, respondents' comments included judgements about structural stability or instability – i.e. whether sociotechnical arrangements for buildings' heating are likely to be 'locked-in' around existing (albeit repurposed) infrastructure (Unruh, 2002), or may reach a tipping-point which would allow for more radical change. For many, incumbent infrastructure was unlikely to lose its dominant status:

> *"[An] incremental approach based on existing networks is the most likely outcome in most places."*
>
> Senior official in a public body

> *"The outcome I consider most likely (though not desirable) is that … change will be slow and uncertain."*
>
> Senior academic physical scientist

Others argued the dominance of national infrastructure could be eroded by 2040 (allowing more radical change thereafter):

> *"Technologies will emerge (and are emerging) that allow for more local initiatives."*
>
> Senior scientist in a NGO

> *"The patchwork of approaches that we are likely to see … mean that radical change by 2060 could be … enabled."*
>
> Senior official in a public body

Another aspect of structural uncertainty is the uncertain role of policy as a driver of change. Some respondents suggest that disruptive change in buildings' heating is predicated on decisive national government action – without this, national infrastructure is likely to prevail:

> *"Unless there are strong and directive signals from government, I don't see… big shifts in heating technologies by then."*
>
> Mid-career academic interdisciplinary researcher

For those anticipating a less decisive role for government, a patchwork mix of solutions is a more likely outcome:

> *"I don't see this as an issue when central gov't direction is likely to be very specific. [A] mix of technologies [is] likely to follow from small-scale experimentation."*

Senior academic social scientist

Other participants emphasised the role of local community agency rather than national government, arguing that where local citizens are motivated and adequately resourced, then a shift to local and community heating systems is possible.

Values

Our analysis revealed that views on the likely role of policy as a driver of change were themselves influenced in part by participants' values, in terms of political questions such as who should drive changes in the energy system. A small number of participants perceive a local governance approach as inherently preferable, as national government inhibits a desirable transition away from national infrastructure:

> *"Whether the governance emerges that allows [local initiatives] to flourish to their full potential given the centralising tendency of UK policy remains to be seen."*

Senior scientist in a NGO

All participants who expressed a normative preference for local governance see a patchwork mix as likely or highly likely, and while some doubt that local, community or municipal provision will dominate by 2040, they consider it possible and desirable in the longer term. By contrast, participants who assume that central government should drive change typically thought the continued dominance of national infrastructure is the most likely outcome in 2040:

> *"In the absence of national policy drivers, it is likely that significant change on heat will not happen until later."*

Senior manager in an industry body

The varied styles of reasoning seen among Round 1 participants help to explain why the majority of participants did not change their views in the second round, and why they also tended not to engage with the arguments of those they disagreed with. For each of the three propositions on heating, less than 20% of the participants changed their answers between rounds. Most of those who did change shifted to the most popular proposition in Round 1 ('patchwork mix') without explaining why they did so. Two participants moved away from this proposition, either because they were persuaded that it would be too expensive, or because they now felt that more evidence is required. Reflecting the difference in values in Round 1 results (in terms of the desirable governance scale), one participant challenged others' assumptions that decisive action by national government was needed to solve the heat challenge, arguing instead that there needs to be a gradual process of demonstration and learning at different levels to steer the heat transition over the next 10-20 years.

4.2 Personal Transport

Introduction

In the UK, as in most developed countries, personal transport is dominated by user-owned conventional (internal combustion engine) vehicles, with nearly 80% of UK households owning a vehicle and approximately 60% of all trips in England taken by car (Department for Transport, 2019). Moreover, the transport sector accounted for 28% of all UK emissions in 2017 (BEIS, 2018). While there are estimated to be over 150,000 ultra-low emission vehicles (i.e. electric, hybrid and hydrogen fuel-cell vehicles) in the UK at present (Department for Transport, 2018), the Committee on Climate Change has argued that adoption rates are too slow to achieve the UK's target of reducing direct emissions from vehicles by 80% by 2050 (Committee on Climate Change, 2019). Alongside a range of options for increasing adoption rates, it has been suggested that changing consumer behaviours and practices may also need to play a role if that target is to be achieved (Brand et al., 2019).

From a consumer perspective, a transition which mainly involves the technological substitution of conventional vehicles with low emission vehicles represents a continuity-based transition logic, whereas a transition in which changes in consumer behaviours and practices play a significant role represents a disruptive transition logic. Survey participants were therefore asked to assess the likelihood of the following distinct propositions:

1. Changes in consumer behaviours / practices, such as reductions in travel, shared ownership, and modal shift (including more use of walking, cycling, and public transport) will play a critical role in the UK's transport transition between now and 2040
2. The UK's transport transition over the 2020s and 2030s will be dominated by technological substitution (e.g. the use of low emission vehicles)

Again, the participants were asked to explain their answers with reference to sources where possible. The Round 1 results are displayed below.

Table 3: The UK transport sector transition to 2040

Personal transport propositions	Highly likely	Likely	Unlikely	Highly unlikely	Cannot say/ undecided	Total valid response*	Extent of consensus	Consensus View
Changes in consumer behaviours / practices, such as reductions in travel, shared ownership, and modal shift (including more use of walking, cycling, and public transport) will play a critical role in the UK's transport transition between now and 2040	11 (11%)	37 (38%)	45 (46%)	4 (4%)	1 (1%)	98	None	N/A
The UK's transport transition over the 2020s and 2030s will be dominated by technological substitution (e.g. the use of low emission vehicles)	30 (30%)	68 (67%)	1 (1%)	1 (1%)	1 (1%)	101	High	Likely/ Highly Likely

* i.e. excluding 'undecided' / 'cannot say' responses.

As Table 3 shows, the sample was approximately evenly divided on the likelihood of whether changes in consumer behaviours / practices will play a critical role in the UK's personal transport transition. In stark contrast, there was very strong consensus that the transition will be dominated by technological substitution, with 97% deeming this likely or highly likely. As with buildings' heating, this suggests that most respondents anticipate that a continuity-based transition logic will play a powerful role.

Parametric Uncertainty

Respondents' comments reveal that the key sources of parametric uncertainty on transport futures relate to differences over the perceived performance and convenience of alternatives to user-owned motor vehicles and the envisaged feasible pace of change. For those who do not consider modal shift (i.e. greater use of walking, cycling, and public transport) likely to play a significant role, key factors include the lack of convenient alternatives, the current cost of public transport, and the challenges associated with changing the regular habits and practices of large sections of the population. Some acknowledged that recent data suggests that vehicle ownership is not rising as fast as previously, but maintained that this is not a widespread change, and looking ahead, it is likely to be limited to particular groups (particularly younger people in urban areas):

> *“Behaviour change is happening at the ‘margins’ which gets lots of publicity. However, the vast majority of the public are not changing their behaviour and are not showing any desire to change their behaviour”*
>
> Senior transport planning specialist in a government body

By contrast, those who believe that behavioural changes could be significant by 2040 tended to focus on other consumer considerations, such as the health benefits associated with cycling, and increasing demand for service-based business models. These participants typically extrapolated from marginal changes in transport behaviours (particularly in urban areas and among younger people) to argue that a decisive turn away from the dominance of user-owned motor vehicles could become mainstream by 2040. As for buildings’ heating, experts holding different views selected different key parameters – or made different assessments about the likely rate of change of key parameters – to form judgements about transport futures.

Structural uncertainty

In terms of structural uncertainties, those who judged it unlikely that consumer practices and behaviours will have a significant impact on the UK’s personal transport transition tended to focus on a relatively narrow problem boundary (including the cost and convenience to consumers), whereas participants holding different views referenced a wider problem framing, including health and local air quality, and also, the potential for sociotechnical interactions to couple together to disruptive effect:

> *“Air pollution concern and regulation will continue to drive [the] move away from internal combustion engines”*
>
> Senior academic social scientist

> *“Congestion in urban areas and other concerns such as health should mean that modal shifts etc. do play a significant role”*
>
> CEO of a NGO

> *“The transition from internal combustion engines … will change the paradigm of ownership.”*

Professor of engineering

Values

As with heating, participants' values on transport futures are revealed in terms of preferences towards who should be responsible for driving change (in terms of individual, community or national decision-makers), and also, a preference for either more social and behavioural solutions, or 'technical fixes':

> *"The onus is on policy to create the context for a low-carbon transport transition. And yes, that means aggressive steps to exclude or marginalise cars and planes."*
>
> Senior academic interdisciplinary researcher

> *"What is needed is fundamental shifts in values"*
>
> Senior manager in an environmental NGO

> *"Of course there will also be a welcome drive to make towns and cities more liveable by slowing traffic down but a hair shirt approach won't wash"*
>
> Director of a government body

However, unlike heating, there is no clear association between respondents' values related to governance and agency, and expected outcomes for transport. For example, those who consider that policy-makers should drive a shift in consumer habits and preferences are approximately evenly split between those who believe that such a shift is likely to occur, and those who think it will remain marginal. Similar divisions are found among those who view consumption practices and behaviours as a matter of personal choice or community-scale decision-making, rather than government intervention. While values informed problem framings for transport – behaviour change as either an individualist or collectivist issue – they did not determine expectations i.e. whether behaviour change would actually play a significant role.

In Round 2 the vast majority of respondents did not change their answers. Only six changes to Likert scale choices were made for each of the transport propositions, and only one of these was a substantial change (from unlikely to likely, for the significance of consumer change, without an explanation). While values do not correspond straightforwardly with expectations, the variation in values observed above may nonetheless help to explain respondents' limited engagement with other views in Round 2, as some simply reiterated their view on the need for consumer choices to reflect community values, or alternatively the need for policy action to promote changes in consumer behaviours and patterns. Round 2 comments also featured further discussion of the significance of niche changes in consumer behaviour and potential interactions between technologies and new societal trends. The speculative and indeterminate nature of these issues, and the way they allow for different problem framings, is potentially another reason why participants were not persuaded by other respondents' perspectives.

5. Discussion

The survey findings offer new understandings of why experts disagree about the future of complex and dynamic sociotechnical systems, and how the Policy Delphi method can be used to map and understand such disagreements. In particular, they reveal that expert expectations about the future of the UK's energy system reflect not only varied interpretations of the evidence base, current trends and policy actions – in terms of parametric and structural uncertainties – but also divergent assumptions and values. Assessments of uncertainty and underlying values are intertwined, in that values shape experts' ordering of the key parameters and the structural relations or problem framings involved. Even so, it is important to consider the different reasons underlying expert disagreements, as they hold different implications for decision-makers and analysts.

The survey was designed to elicit these differences in terms of different expectations about the role of alternative (continuity-based and disruptive) transition logics in UK energy system change. The focus was on two particularly challenging and contested parts of the energy system: buildings' heating and personal transport. For both cases, a majority of respondents considered that, at least from a consumers' perspective, a broadly continuity-based transition was more likely than a disruptive one, but with some emerging disruptive features. Survey participants' more detailed responses reflected the many uncertainties and complex interdependencies involved in assessing likely futures.

In assessing these uncertainties and complexities, experts' disagreements are not restricted to judgements over parametric value. Rather, different ways of assessing issues such as the rate of technological change are evident, so that differences over apparently commensurable parameters cannot be reconciled by more and better evidence alone. Similarly, expert views reflect a range of structural uncertainties, including complex sociotechnical interactions within the system, varied system boundaries, and the endogenous role of policy and other human agency in shaping outcomes. Across both cases, those who believe that more disruption-based outcomes are likely tended to consider a wider problem framing than others, and Trutnevyte et al. (2016) argued that including a broad range of structural uncertainties in energy futures analysis was useful to reflect the wide span of possible outcomes. Our results suggest that alternative scenario logics based on continuity-led and disruptive narratives offer useful proxies for capturing a wide range of expert views and reasoning.

Differences in experts' values also emerged in the survey data. While participants did not always explicitly reference their normative views, comments on issues such as problem uncertainty, urgency, agency and societal response revealed underlying value differences. For instance, in personal transport, comments arguing for government leadership reflect a hierarchist worldview, while those calling for a change in consumer values reflect egalitarian or individualist perspectives (Douglas and Wildavsky, 1982).

Values were manifested, for example, in terms of experts' normative associations with local or national governance of change, or preferences for mainly social or technical solutions. As anticipated in the expertise literature, experts' judgements about the future are informed by the values they hold – such that those who hold positive normative associations with local and distributed governance of buildings' heating expect a patchwork mix of solutions across different scales to emerge (Nelkin, 1975; Thompson, 1984; Jasanoff, 1990; Sarewitz, 2004; Hulme, 2009; Pye et al., 2018). However, there was no clear association between values and expected outcomes for the transport case. Overall, the evidence here suggests that although values inform and shape experts' views, they don't fully account for expert disagreement.

For both topics, only a minority of the participants changed their views between rounds. While this may in part be due to participant groups lacking trust in the context of anonymised surveys (Wright and Rowe, 2011), the comments reveal a range of explanations, including diverging parametric uncertainty prioritisation, and diverging responses to structural features such as the appropriate level of agency – differences which are underpinned by value differences.

Finally, while there were some instances of 'epistemic challenge' between participants which could provoke debate and encourage learning (Rip, 2003; Kattirtzi, 2016), these were rare, and overall the findings suggest limits to the potential for expert elicitation methods such as Policy Delphi to resolve policy disputes on contested topics. As Miles et al. (2016) noted, Policy Delphi is most appropriate as a decision support tool within a wider forecasting process, alongside complementary methods such as discursive workshops and formal modelling.

Conclusions

For challenging and contested areas of sociotechnical change, expert disagreements are unlikely to be resolved through the generation and synthesis of more and better evidence alone. As Pielke Jr and Stirling (Pielke, Jr, 2007; Stirling, 2010) both noted, this implies a need to make value differences more explicit in public policy processes, and to transparently articulate and compare alternative solutions reflecting different values.

For scenario developers, our results suggest a need to go beyond parametric and structural uncertainties and reflect value and framing differences, using both qualitative and quantitative analysis. It is important that decision-makers and analysts, in their shared concern for evidence based decision-making, develop methods which acknowledge the diversity of expert perspectives and reasoning on the key uncertainties and choices involved. By setting out the diversity of expert reasoning on contested policy issues, Policy Delphi can help decision-makers more fully appreciate the uncertainties, problem framings and evidence bases involved, and how they are associated with different epistemic and normative perspectives.

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References

Banwell, C., Hinde, S., Dixon, J., Sibthorpe, B., 2005. Reflections on expert consensus: A case study of the social trends contributing to obesity. *European Journal of Public Health* 15, 564–568. https://doi.org/10.1093/eurpub/cki034

BEIS, 2018. Digest of UK Energy Statistics (DUKES). London: HM Government, Department of Business, Energy and Industrial Strategy.

Bolger, F., Stranieri, A., Yearwood, J., 2011. Does the Delphi process lead to increased accuracy in group-based judgmental forecasts or does it simply induce consensus amongst judgmental forecasters? *Technological Forecasting and Social Change* 78, 1671–1680. https://doi.org/10.1016/J.TECHFORE.2011.06.002

Bradfield, R.M., 2008. Cognitive Barriers in the Scenario Development Process. *Advances in Developing Human Resources* 10(1), 198–215. https://doi.org/10.1177/1523422307313320

Brand, C., Anable, J. and Morton, C. 2019. Lifestyle, efficiency and limits: modelling transport energy and emissions using a socio-technical approach. *Energy Efficiency*. 12(1), 187–207. https://doi.org/10.1007/s12053-018-9678-9

Bryman, A. (2016). Social Research Methods. 5th Edition. Oxford, Oxford University Press.

Chaudry, M., Abeyesekera, M., Hosseini, S. H. R., Jenkins, N., and Wu, J., 2015. Uncertainties in decarbonising heat in the UK. *Energy Policy* 87: 623-640.

Coates, J.F., 1975. In defense of Delphi: A review of Delphi assessment, expert opinion, forecasting, and group process by H. Sackman. *Technological Forecasting and Social Change* 7, 193–194. https://doi.org/10.1016/0040-1625(75)90058-X

Collingridge, D., Reeve, C., 1986. *Science Speaks to Power: The Role of Experts in Policy Making*. London: Pinter.

Committee on Climate Change, 2016. *Next steps for UK heat policy.* London: Committee on Climate Change.

Committee on Climate Change, 2019. *Net Zero – The UK's contribution to global warming.* London: Committee on Climate Change.

Dayé, C. (2018). How to train your oracle: The Delphi method and its turbulent youth in operations research and the policy sciences. *Social Studies of Science*, 48(6), 846–868. https://doi.org/10.1177/0306312718798497

de Loë, R.C., 1995. Exploring complex policy questions using the Policy Delphi: A multi-round, interactive survey method. *Applied Geography* 15, 53–68. https://doi.org/10.1016/0143-6228(95)91062-3

de Loë, R.C., Melnychuk, N., Murray, D., Plummer, R., 2016. Advancing the state of Policy Delphi practice: a systematic review evaluating methodological evolution, innovation, and opportunities. *Technological Forecasting and Social Change* 104, 78–88. https://doi.org/10.1016/J.TECHFORE.2015.12.009

Department for Transport, 2019. *Percentage of households with cars by income group, tenure and household composition: Table A47*. London: HM Government.

Department for Transport, 2018. *The Road to Zero Next steps towards cleaner road transport and delivering our Industrial Strategy*. London: HM Government.

Derbyshire, J., Wright, G., 2014. Preparing for the future: Development of an 'antifragile' methodology that complements scenario planning by omitting causation. *Technological Forecasting and Social Change* 82, 215–225. https://doi.org/10.1016/J.TECHFORE.2013.07.001

Dorr, A., 2017. Common errors in reasoning about the future: Three informal fallacies. *Technological Forecasting and Social Change* 116, 322–330. https://doi.org/10.1016/J.TECHFORE.2016.06.018

Douglas, M. and Wildavsky, A. 1982. *Risk and Culture: An Essay on the Selection of Technical and Environmental Dangers*. Berkeley and London: University of California Press.

Energy Institute, 2017. *Energy Barometer 2017*. London.

Eyre, N. and Baruah, C. 2015. Uncertainties in future energy demand in UK residential heating. *Energy Policy* 87: 641-653. https://doi.org/10.1016/j.enpol.2014.12.030

Funtowicz, S.O., Ravetz, J.R., 1993. Science for the post-normal age. *Futures* 25, 739–755. https://doi.org/10.1016/0016-3287(93)90022-L

Geels, F.W., 2002. Technological transitions as evolutionary reconfiguration processes: a multi-level perspective and a case-study. *Research Policy* 31(8): 1257-1274.

Ghanem, D.A., Haggett, C., 2011. Shaping people's engagement with microgeneration technology: the case of solar photovoltaics in UK homes, in: Devine-Wright, P. (Ed.), *Renewable Energy and the Public: From NIMBY to Participation*. London: Earthscan, pp. 150–165.

Gordon, T.J., 1994. The Delphi Method, in Glenn, J.C and Gordon, T.J (Eds.), AC/UNU Millennium Project: Futures Research Methodology. American Council for the UN.

Hofman, P.S., Elzen, B., 2010. Exploring system innovation in the electricity system through sociotechnical scenarios. *Technology analysis & strategic management* 22(6) 653–670. https://doi.org/10.1080/09537325.2010.496282

Howard, R., Bengherbi, Z., 2016. *Too Hot to Handle? How to decarbonise domestic heating*. London: Policy Exchange.

Hughes, N., Strachan, N., 2010. Methodological review of UK and international low carbon scenarios. *Energy Policy* 38, 6056–6065. https://doi.org/10.1016/J.ENPOL.2010.05.061

Hughes, N., Strachan, N., Gross, R., 2013. The structure of uncertainty in future low carbon pathways. *Energy Policy* 52, 45–54. https://doi.org/10.1016/J.ENPOL.2012.04.028

Hughes, T.P., 1983. Networks of power: electrification in Western society, 1880-1930. Baltimore: Johns Hopkins University Press.

Hulme, M., 2009. *Why We Disagree About Climate Change: Understanding Controversy, Inaction and Opportunity*. Cambridge: Cambridge University Press.

IPCC, 2018. Special Report: Global Warming of 1.5°C. Geneva: United Nations International Panel on Climate Change. Available from http://www.ipcc.ch/report/sr15 Last accessed 23-09-19.

Jasanoff, S., 2004. *States of Knowledge: The Co-Production of Science and the Social Order.* Oxford: Routledge.

Jasanoff, S., 1990. *The Fifth Branch: Science Advisers as Policymakers*. Harvard University Press, Cambridge, Massachusetts.

Kattirtzi, M., 2016. Providing a “challenge function”: Government social researchers in the UK’s Department of Energy and Climate Change (2010–2015). *Palgrave Communications* 2(9). https://doi.org/10.1057/palcomms.2016.64

Kuhn, T.S., 1970. *The Structure of Scientific Revolutions*. Chicago: University of Chicago Press.

Landeta, J., Barrutia, J., 2011. People consultation to construct the future: A Delphi application. *International Journal of Forecasting* 27, 134–151. https://doi.org/10.1016/J.IJFORECAST.2010.04.001

Li, F.G.N., 2017. Actors behaving badly: Exploring the modelling of non-optimal behaviour in energy transitions. Energy Strategy Review 15, 57–71. https://doi.org/10.1016/J.ESR.2017.01.002

Li, F.G.N., Pye, S., 2018. Uncertainty, politics, and technology: Expert perceptions on energy transitions in the United Kingdom. *Energy Research and Social Science* 37, 122–132. https://doi.org/10.1016/J.ERSS.2017.10.003

McDowall, W., Trutnevyte, E., Tomei, J., Keppo, I., 2014. *UKERC Energy Systems Theme: Reflecting on Scenarios*. London: UKERC.

Miles, I., Saritas, O., Sokolov, A., 2016. *Foresight for Science, Technology and Innovation*. Switzerland: Springer International Publishing, Cham. https://doi.org/10.1007/978-3-319-32574-3

Nelkin, D., 1975. The political impact of technical expertise. *Social Studies of Science* 5, 35–54.

Pätäri, S., 2010. Industry- and company-level factors influencing the development of the forest energy business — insights from a Delphi Study. *Technological Forecasting and Social Change* 77, 94–109. https://doi.org/10.1016/J.TECHFORE.2009.06.004

Pielke, Jr, R.A., 2007. *The Honest Broker*. Cambridge: Cambridge University Press. https://doi.org/10.1017/CBO9780511818110

Pinch, T.J., 1992. Opening black boxes: science, technology and society. *Social Studies of Science* 22, 487–510.

PwC, 2016. *Capturing value from disruption Technology and innovation in an era of energy transformation*. London: PwC.

Pye, S., Li, F.G.N., Petersen, A., Broad, O., McDowall, W., Price, J., Usher, W., 2018. Assessing qualitative and quantitative dimensions of uncertainty in energy modelling for policy support in the United Kingdom. *Energy Research and Social Science* 46, 332–344. https://doi.org/10.1016/J.ERSS.2018.07.028

Rip, A., 2003. Constructing Expertise: In a Third Wave of Science Studies? *Social Studies of Science* 33, 419–434. https://doi.org/10.1177/03063127030333006

Sarewitz, D., 2004. How science makes environmental controversies worse. *Environmental Science and Policy* 7, 385–403. https://doi.org/10.1016/j.envsci.2004.06.001

Small, M., 2011. "How to Conduct a Mixed Methods Study: Recent Trends in a Rapidly Growing Literature." *Annual Review of Sociology* 37(1): 57-86. https://doi.org/10.1146/annurev.soc.012809.102657

Steinert, M., 2009. A dissensus based online Delphi approach: An explorative research tool. *Technological Forecasting and Social Change* 76, 291–300. https://doi.org/10.1016/J.TECHFORE.2008.10.006n

Stirling, A., 2008. "Opening Up" and "Closing Down." *Science, Technology and Human Values* 33, 262–294. https://doi.org/10.1177/0162243907311265

Stirling, A., 2010. Keep it complex. *Nature* 468, 1029–1031. https://doi.org/10.1038/4681029a

Strachan, N., Pye, S., Kannan, R., 2009. The iterative contribution and relevance of modelling to UK energy policy. *Energy Policy* 37, 850–860. https://doi.org/10.1016/J.ENPOL.2008.09.096

Tapio, P., 2003. Disaggregative Policy Delphi: Using cluster analysis as a tool for systematic scenario formation. *Technological Forecasting and Social Change* 70, 83–101. https://doi.org/10.1016/S0040-1625(01)00177-9

Thompson, M. 1984. Among the Energy Tribes: A Cultural Framework for the Analysis and Design of Energy Policy. *Policy Sciences* 17(3), 321-339.

Thompson, M. 1990. 'Among the energy tribes' in M. Schwarz and M. Thompson, *Divided We Stand: Redefining Politics, Technology and Social Choice*, New York / London, Harvester Wheatsheaf.

Trutnevyte, E., McDowall, W., Tomei, J., Keppo, I., 2016. Energy scenario choices: Insights from a retrospective review of UK energy futures. *Renewable and Sustainable Energy Reviews* 55, 326–337. https://doi.org/10.1016/J.RSER.2015.10.067

Unruh, G.C. 2002. Escaping carbon lock-in. *Energy Policy* 30(4), 317-325.

van de Linde, E., van der Duin, P., 2011. The Delphi method as early warning: Linking global societal trends to future radicalization and terrorism in The Netherlands. *Technological*

Forecasting and Social Change 78, 1557–1564. https://doi.org/10.1016/J.TECHFORE.2011.07.014

Van der Vleuten, E., Högselius, P., 2012. Resisting Change? The transnational dynamics of European energy regimes, in: Verbong, G., Loorbach, D. (Eds.), *Governing the Energy Transition: Reality, Illusion or Necessity?* London: Routledge pp. 75–100.

Wilson, C., 2018. Disruptive low-carbon innovations. *Energy Research and Social Science* 37, 216–223. https://doi.org/10.1016/J.ERSS.2017.10.053

Winner, L., 1980. Do artifacts have politics? *Daedalus* 109 (1): 121-136.

Winskel, M., 2018. Beyond the disruption narrative: Varieties and ambiguities of energy system change. *Energy Research and Social Science* 37, 232–237. https://doi.org/10.1016/J.ERSS.2017.10.046

Winskel, M., Radcliffe, J., 2014. The rise of accelerated energy innovation and its implications for sustainable innovation studies: A UK perspective. *Science and Technology Studies* 27, 8–33.

Wright, G., Rowe, G., 2011. Group-based judgmental forecasting: An integration of extant knowledge and the development of priorities for a new research agenda. *International Journal of Forecasting* 27, 1–13. https://doi.org/10.1016/j.ijforecast.2010.05.012

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